Electron lens overview

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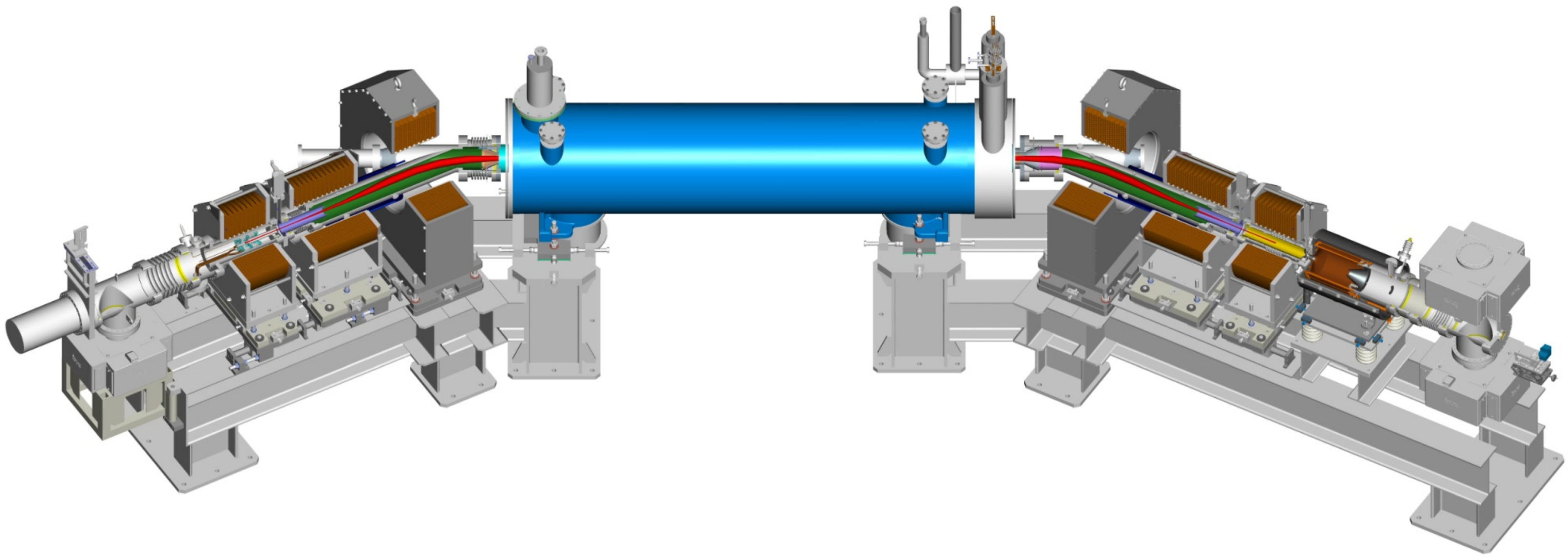
W. MacKay, M. Mapes, C. Montag, B. Oerter, M. Okamura, A.I. Pikin,
D. Raparia, Y. Tan, R. Than, J. Tuozzolo, and W. Zhang

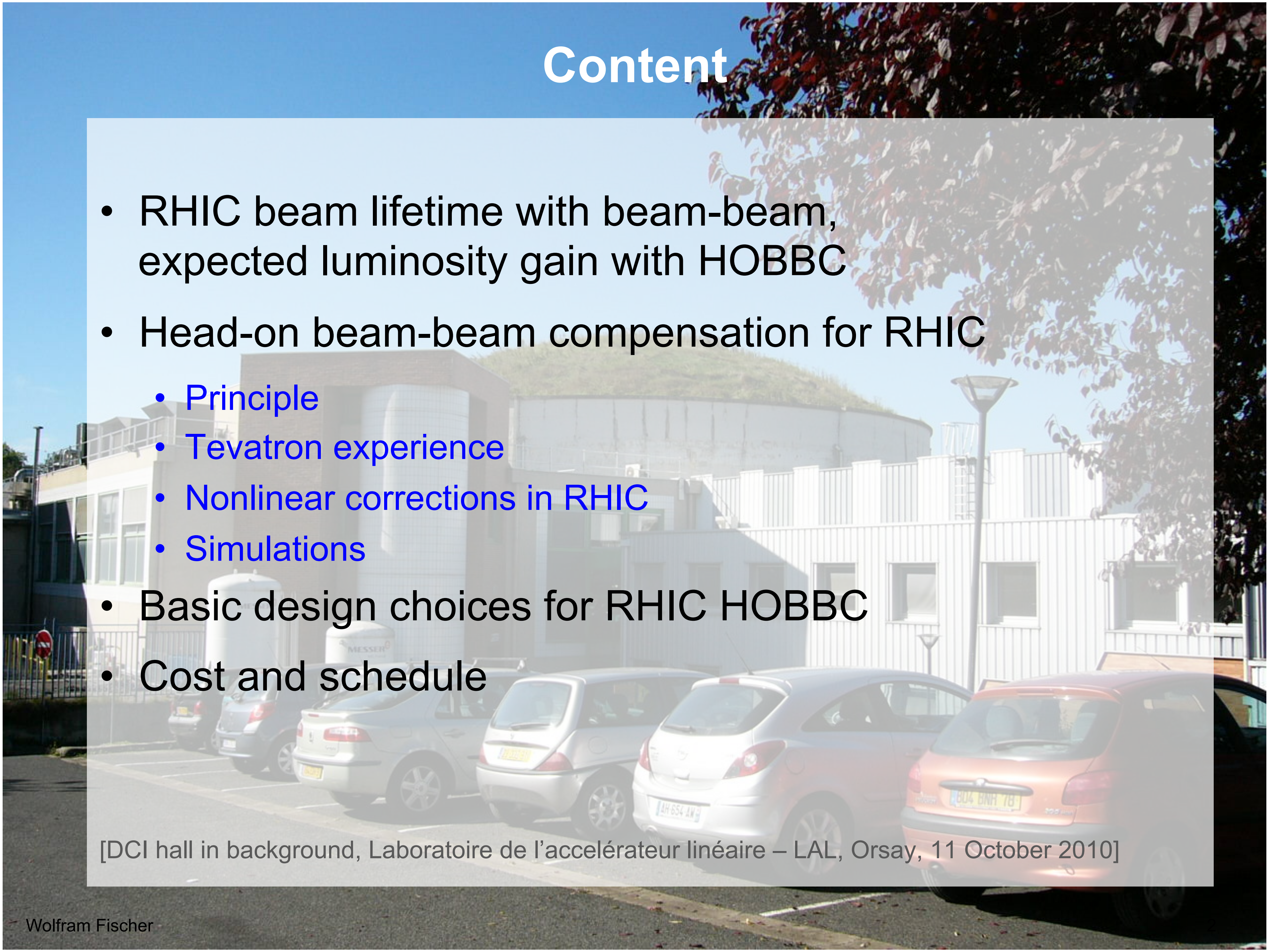


BROOKHAVEN NATIONAL LABORATORY

15 November 2010
CAD MAC-07, BNL

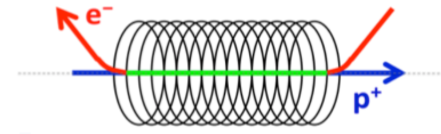
Content

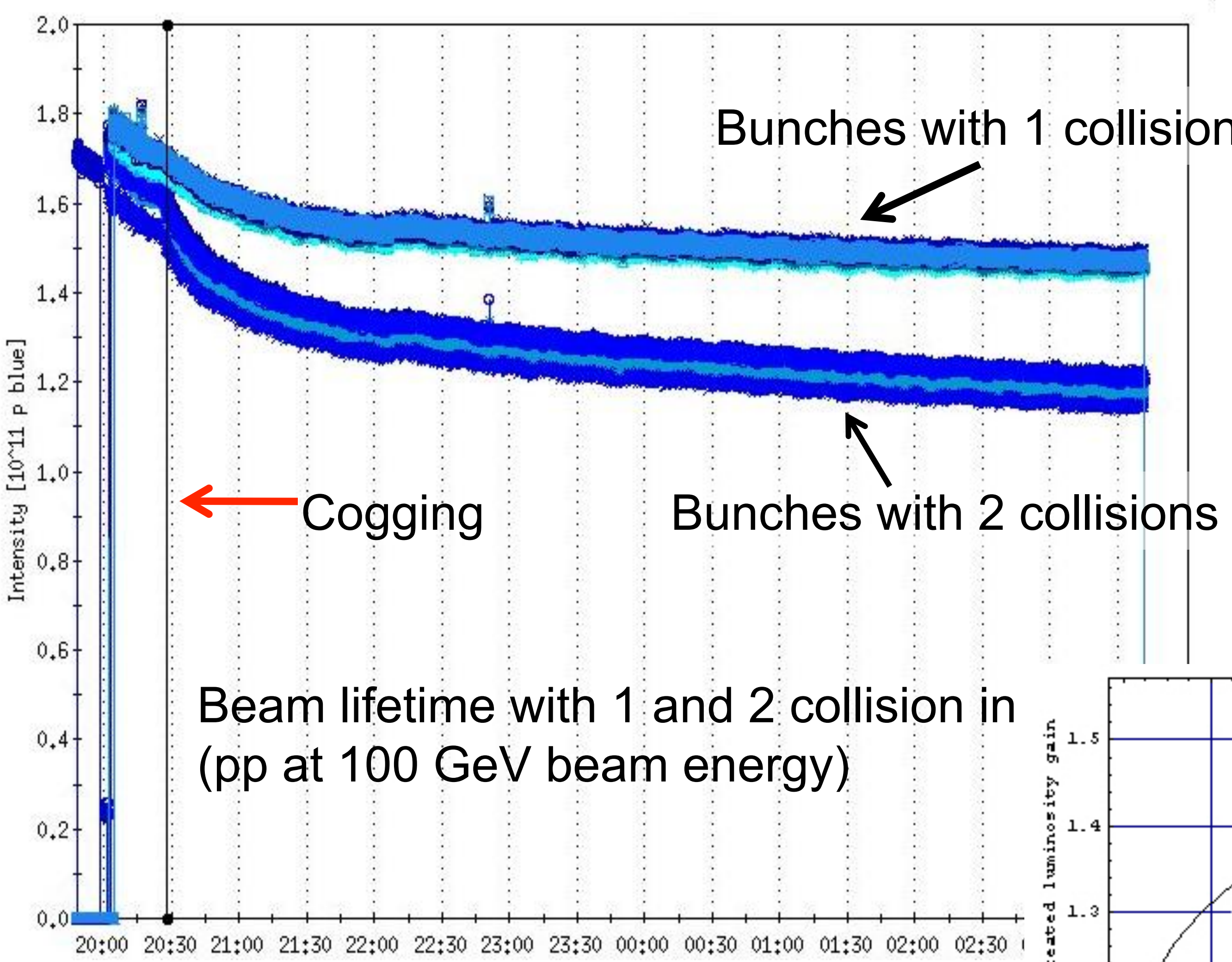
- RHIC beam lifetime with beam-beam, expected luminosity gain with HOBBC
- Head-on beam-beam compensation for RHIC
  - Principle
  - Tevatron experience
  - Nonlinear corrections in RHIC
  - Simulations
- Basic design choices for RHIC HOBBC
- Cost and schedule



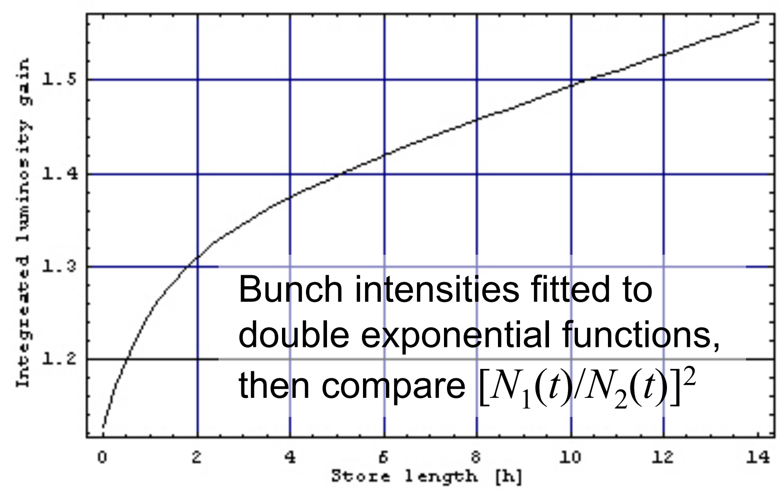
[DCI hall in background, Laboratoire de l'accelérateur linéaire – LAL, Orsay, 11 October 2010]

Luminosity Gain with e-lenses (I)

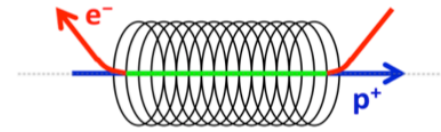




- Plot shows the measured proton beam lifetime with 1 and 2 collisions in RHIC.
- If 1 of 2 collisions can be compensated, gain up to ~50% in integrated luminosity <u>under current conditions.</u>



Luminosity Gain with e-lenses (II)



1. More luminosity can be gained with an increase in the bunch intensity:

$$L = \frac{f_c N_b^2}{4\pi\, \varepsilon\, \beta^*}$$

- If 1 of 2 collisions can be compensated, then N_p can be doubled while total beam-beam $\xi \sim N_p/\varepsilon$ is maintained.

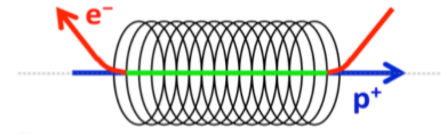
- This would yield a factor of 4; expect in practice <u>up to a factor of 2</u> due to incomplete compensation and other intensity dependent effects

2. Increase of proton bunch intensity requires:

- Upgrade of the polarized proton source (presentation A. Zelenski)
- Upgrades in RHIC

done: beam dump; **in progress:** Safety Assessment Document, instrumentation, ramp transmission, collimation

Luminosity gain with single e-lens



A single electron lens yields half of the luminosity gain of two electron lenses.

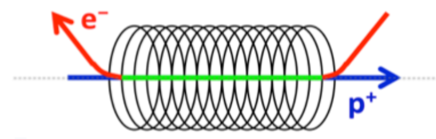
- An increase in the
  Blue (Yellow) bunch intensity,
  leads to an increase in the
  Yellow (Blue) beam-beam parameter,
  which can be compensated by a
  Yellow (Blue) electron lens
- Luminosity is proportional to both Blue and Yellow bunch intensity

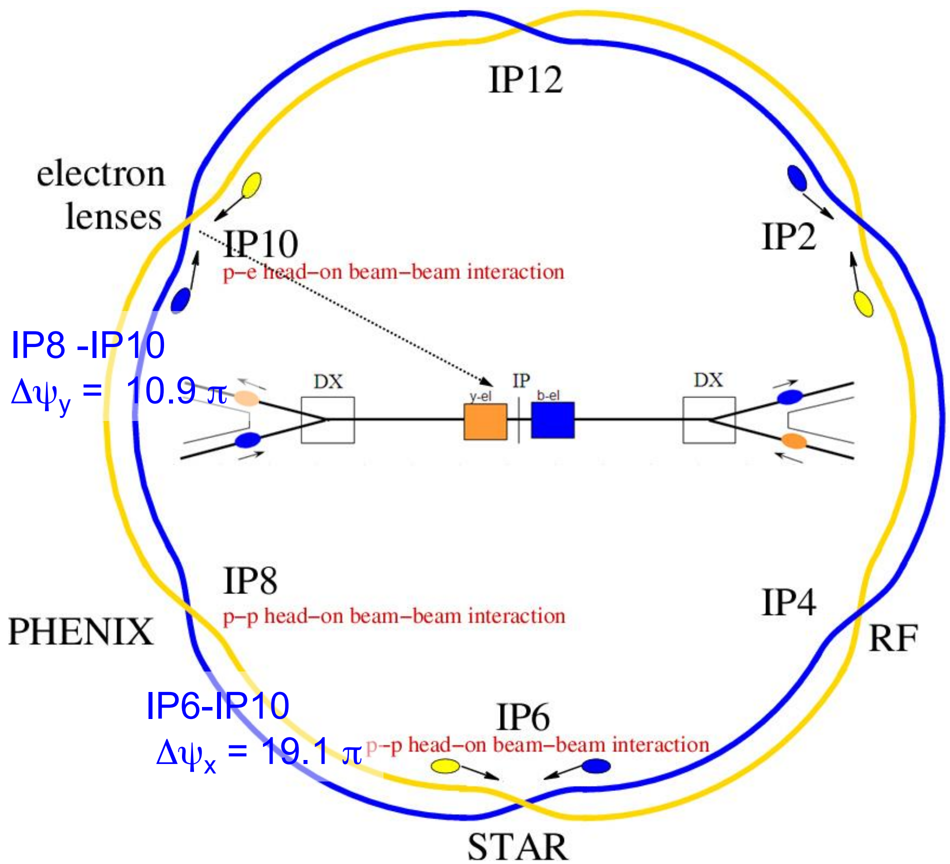
$$\xi_{B,Y} = \frac{1}{4\pi} \frac{N_{Y,B}}{\varepsilon_{rms,Y,B}}$$

$$L = \frac{f_c N_B N_Y}{4\pi \varepsilon_{rms} \beta^*} F\left(\frac{\sigma_s}{\beta^*}, \theta \right)$$

Two lenses are operationally easier since Blue and Yellow superconducting solenoids compensate each other for x-y coupling and spin rotations.

Electron lenses in RHIC





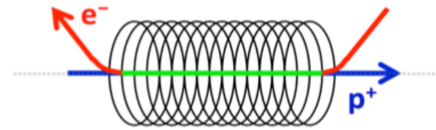
Basic idea:
In addition to 2 beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.

2 electron lenses installed in Tevatron, not used for head-on beam-beam compensation

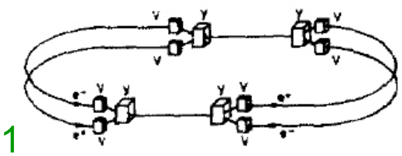
Exact compensation possible for:
- short bunches
- $\Delta\psi_{x,y}$ = kπ between p-p and p-e collision
- no nonlinearities between p-p and p-e
- same amplitude dependent kick from p-p, p-e

Only approximate realization possible

Head-on beam-beam compensation in DCI

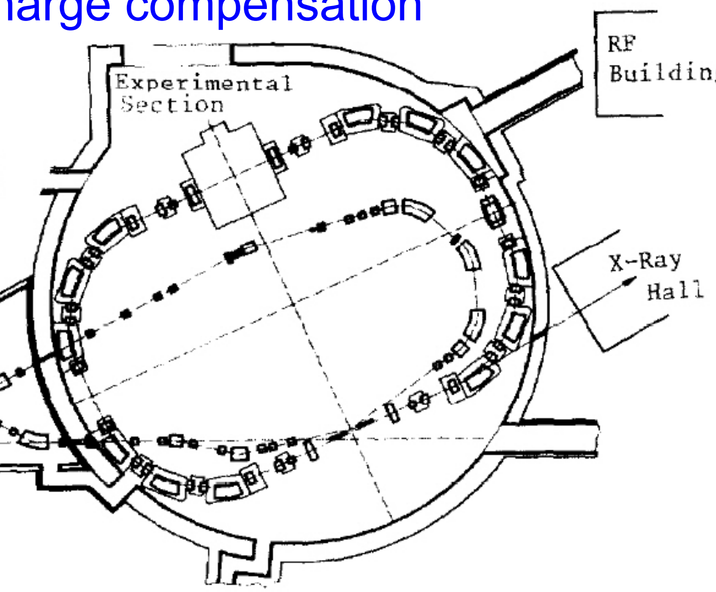


- Head-on beam-beam compensation was only tested in DCI (~1975)
  - 4-beam collider ($e^+e^-e^+e^-$) for complete space charge compensation
  - Main parameters:
    - Circumference 94.6 m
    - Energy 1.8 GeV
    - Beam-beam ξ ~0.05-0.1
    - Luminosity (design) ~10^{32} $cm^{-2}s^{-1}$



4 Beam Scheme

  - Luminosity fell short of expectations by 2 orders of magnitude
    (2- and 4-beam luminosity about the same)
  - Short-fall attributed to strong coherent effects

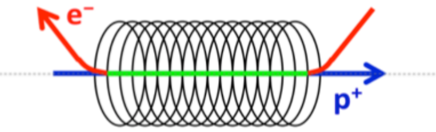


The Orsay Storage Ring Group, "Status report on D.C.I.", PAC77

- RHIC HOBBC is different from DCI HOBBC
  - Indirect compensation with single pass e-lens beam does not allow for coherent coupling between e-lens and proton beam
  - Beam-beam parameter in RHIC smaller by order of magnitude

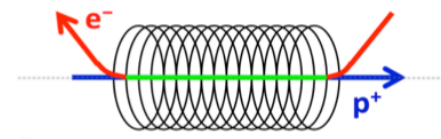
➔ Expect coherent effects to be absent (e-lens/p-beam), or manageable (p-beam/p-beam)

Tevatron e-lens experience

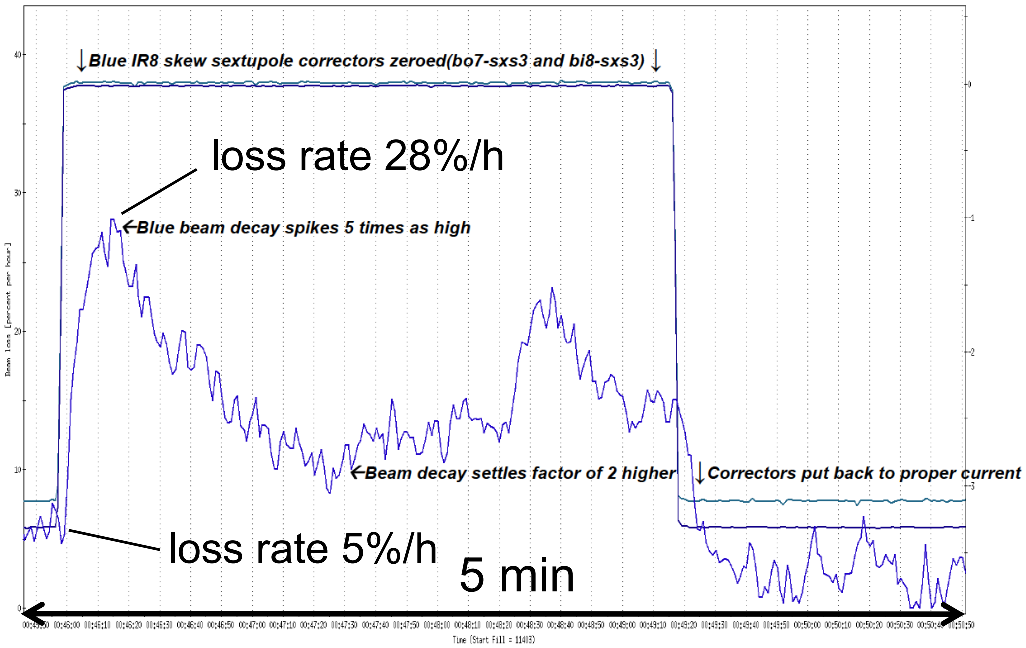


- Details in presentation of C. Montag
- TEL experience shows that electron lens can be a reliable accelerator component (no Tevatron stores lost)
- Observed tune shift and spread with Gaussian profile as expected
- Electron current fluctuations of 10^{-3} can be tolerated
- With Gaussian profile offset does not lead to reduction in beam lifetime

Nonlinear IR corrections in RHIC

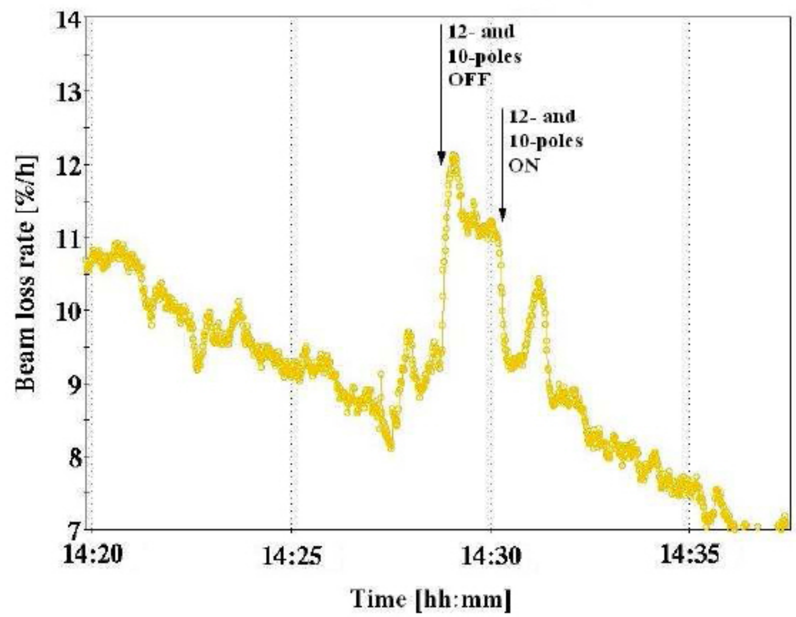


- Use 6-pole, skew 6-pole, 8-pole corrections (IR6 and IR8)
- Setting based on measured tune shifts from orbit bumps in triplets



[F. Pilat et al., PAC'05; C. Zimmer APEX10]

- Have used 10- and 12-poles in 100 GeV pp operation (IR6 and IR8)
- Settings found iteratively based on observed beam loss rate
- *L* +4.3% with 1 beam corrected

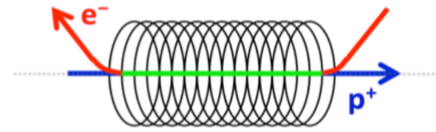


[presented at IPAC10]

High order nonlinear corrections are possible

(beam-beam different from magnet errors).

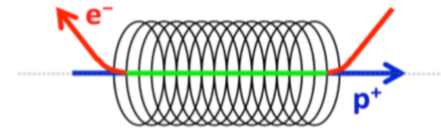
Beam-beam simulations

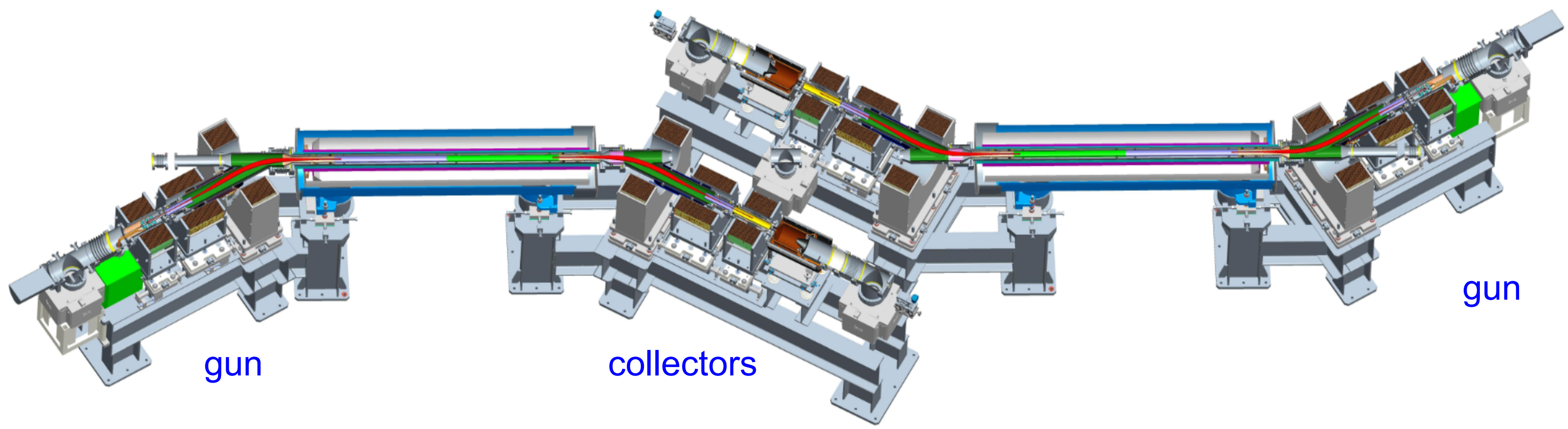


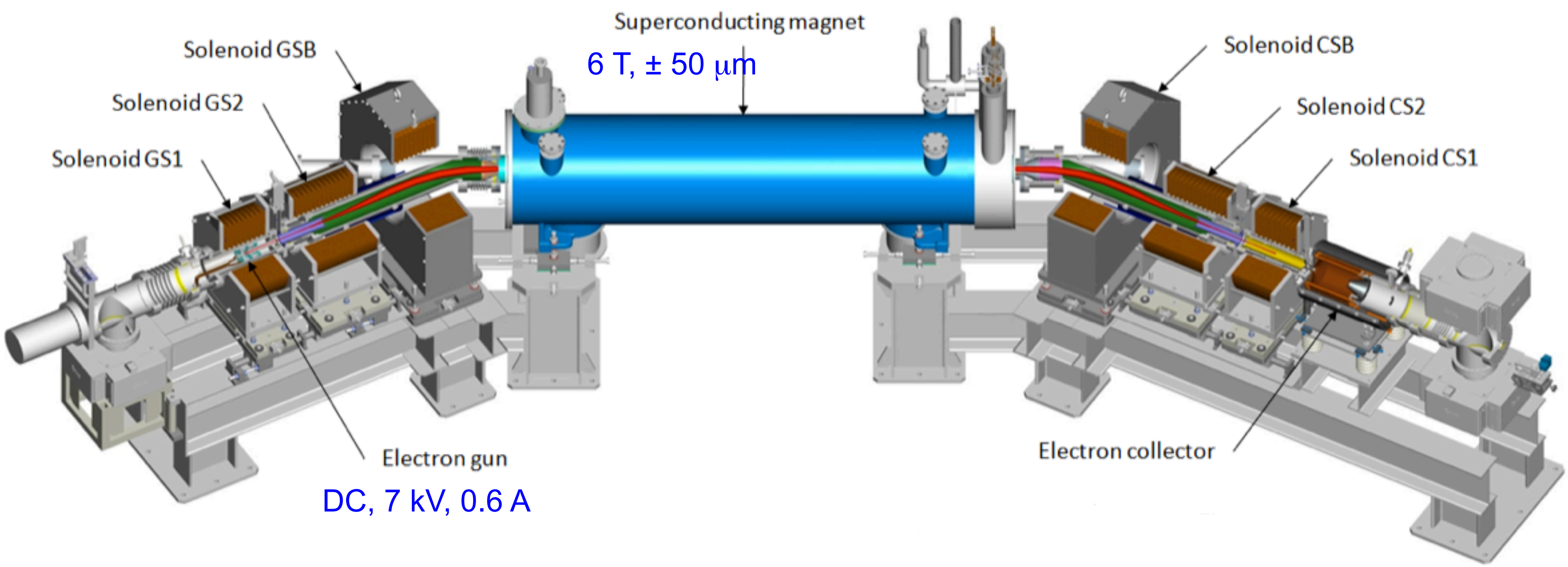
- Presentation by Y. Luo

- Simulations cannot predict beam lifetime of hadron beams with important contributions from nonlinear dynamics effects (beam-beam, magnet errors, parameter modulations)
- Use a number of measures that are known to correlate with long-term stability but no single measure gives decisive information (tune footprints, tune and amplitude diffusion, dynamic aperture, beam lifetime, emittance growth)
- All known measures are still useful for making relative comparisons between different situations
- For absolute predictions simulations must be benchmarked with existing data (open problem for beam lifetime)
- Large amounts of CPU power are generally available

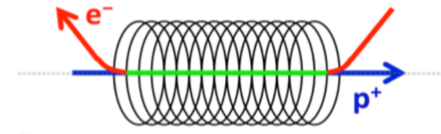
RHIC electron lens





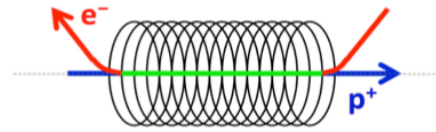


Basic design decisions



1. Electron lenses in IR10
   smallest distance to IP8 head-on beam-beam interaction (nonlinearities), available space
2. Both lenses in common area
   main solenoids compensate each other for coupling and spin, $\beta_x = \beta_y$ at e-lens locations
   drawback: β-functions relatively small (<= 10 m)
3. DC beam for compensation
   avoids noise introduced with HV switching (have pulsed operation for diagnostics)
4. Superconducting main solenoid
   need high field to match electron and proton beam size
5. Field straightness correctors incorporated in sc main solenoid
   compact solenoid
6. Transport solenoids and orbit correctors warm
   capital cost lower than for sc (sc transport solenoids with break-even time 5-10 years)
7. Diagnostics
   basic diagnostic consists of BPMs and RHIC instrumentation (BTF, lifetime),
   working on bremsstrahlung and electron halo detection as alignment monitor

Requirement for electron lens



1. Electron beam size in the main solenoid

    RMS beam size: 0.3 mm - 0.8 mm (issue: relatively small)

2. Gaussian shape of electron beam

    good fit to 3 σ (issue: cathodes have limited size)

3. Straightness of magnetic field in main solenoid

    target of ± 50 μm after correction (issue: good overlap of e and p beam)

4. Steering electron beam in e-lens

    maximum shifting : ± 5 mm in X and Y planes

    maximum angle : 0.1 mrad

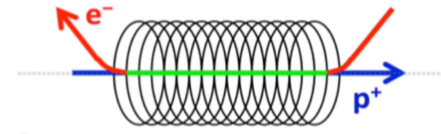
5. Stability in electron current

    power supplies stability better than 10^{-3}

6. Overlap of electron and proton beams

    robust real-time measurement with resolution better than 100 μm

Funding, cost, and schedule

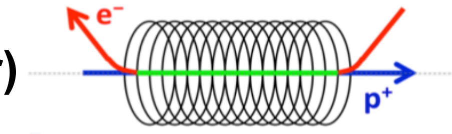


- 2 lenses funded as Accelerator Improvement Projects
  (1 ARRA + 1 regular)

- Recent DOE annual review of ARRA projects (10/04 – 10/05/2010)
  - emphasis on cost on schedule
  - seven recommendations on project management
  - responded to 3 with deadline 11/01/2010 (others have later deadline)

- Recent review of superconducting solenoid (10/20/2010)
  - focus on technical solution
  - nine recommendations, were evaluated
  - talk by R. Gupta on superconducting solenoid

RHIC electron lenses – 2 AIPs (1 ARRA + 1 regular)



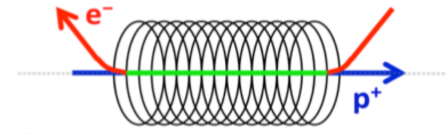
1st electron lens (ARRA AIP):

- Funding: $4.0M (06/25/09)
- Pacing item: superconducting solenoid
  - Had planned to purchase in industry
  - Received only 1 bid from 9 bidders contacted
    (various reasons for no bids – missing production capacity, exchange rate, …)
  - Bid at about 3x budgeted value (budget for sc solenoid guided by 2 benchmarks: EBIS spare solenoid, Tevatron solenoids for electron lens)
  - Failed solenoid bidding also delayed project
  - Solenoid now build in Superconducting Magnet Division
    (allows for technically better magnet)
- Expected completion: 11/2012

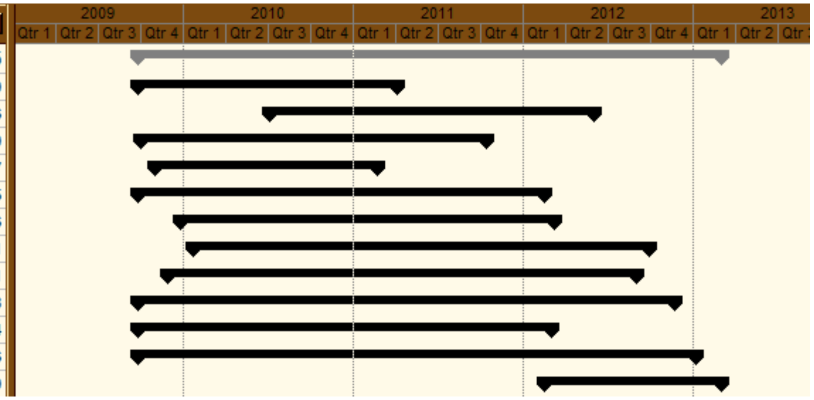
2nd electron lens (AIP):

- Funding: $3.1M (planned for FY2011/12 AIP)
- Expected completion: 11/2012 (same as 1st lens)

Schedule



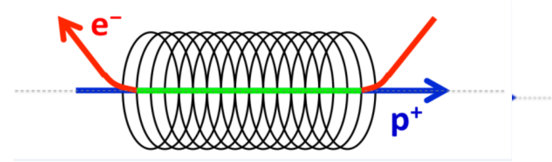
	Task Name	Start	Finish	ARRA AIP Cost	AIP #2 Cost	ARRA AIP Cost AIP #2 Cost
0	− RHIC e-lenses	Thu 6/25/09	Sat 12/1/12	$3,904,219	$3,075,586	$6,979,805
1	+ Funding e-Lens System Milestones	Thu 6/25/09	Wed 1/5/11	$0	$0	$0
6	+ Super Conducting Main Solenoids	Mon 4/5/10	Thu 3/1/12	$1,102,909	$394,427	$1,497,336
31	+ Warm Magnets	Wed 7/1/09	Tue 7/12/11	$209,080	$155,250	$364,330
63	+ Electron Guns	Thu 7/30/09	Tue 11/23/10	$48,588	$20,878	$69,467
70	+ Electron Collectors & Mechanical Supports	Thu 6/25/09	Mon 11/14/11	$255,917	$115,938	$371,855
128	+ Power Supplies	Thu 9/24/09	Wed 12/7/11	$996,916	$840,080	$1,836,996
203	+ Vacuum system	Thu 10/22/09	Wed 6/27/12	$584,800	$713,141	$1,297,941
316	+ Beam Instrumentation	Thu 8/27/09	Wed 5/30/12	$457,136	$694,505	$1,151,641
390	+ Controls	Thu 6/25/09	Mon 8/20/12	$109,424	$110,724	$220,148
578	+ Conventional Facilities	Thu 6/25/09	Wed 11/30/11	$108,804	$0	$108,804
606	+ Installation	Thu 6/25/09	Fri 10/5/12	$30,643	$30,643	$61,286
675	+ Susbystem Test and Commissioning	Tue 11/15/11	Sat 12/1/12	$0	$0	$0



Schedule (about 700 task lines) developed by the system experts and the scheduler.

Tunnel installation planned for summer 2012 for commissioning in Run-13

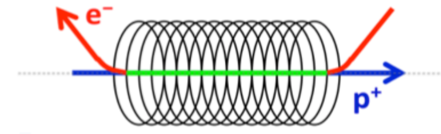
Major procurements



Major procurements: item >$100k

	Major Procurements									
WBS		Planned cost	committed cost	Requisition released	Planned P.O. Date	Actual P.O. date	Purchase Order/Req	Planned delivery	P.O. delivery date	Actua eliver
1.2	Superconducting solenoid		1497000	n/a	12/15/2009	5/1/2010	n/a	10/25/2011		
1.6	Collector Power supplies	351400	351400	12/28/2009	6/30/2010	7/16/2010	p.o. 161911	5/27/2011	7/16/2011	
1.3	Warm Magnets	279000	199400	7/16/2010	9/7/2010	9/13/2010	p.o. 174739	1/7/2011	3/30/2011	
1.6	Warm solenoid power supplies	390000		8/13/2010	10/25/2010		req 171237	7/29/2011		
1.6	long & short corrector power supplies	108000			3/24/2011			8/2/2011		
1.6	quench detection (fringe, long trim, main coils, chassis)	172000			3/24/2011			8/2/2011		
	the solenoid value is burdened, all others are direct cost					**in case of multiple deliveries, dates refer to first unit**				

C-AD MAC-06 23-25 March 2009



Recommendations on electron lenses

- The committee encourages C-AD to support their electron lens R&D efforts with a close follow-up of the Tevatron experience.

Response: Participated in TEL experiments with Gaussian profiles (A. Valishev, C. Montag). See presentation C. Montag.

- Prepare a detailed commissioning plan and testing program already in the design phase of the electron lens.

Response: Not yet, recent focus still on hardware. Plan to do.

- The committee supports the suggested massive simulation effort, but recommends to first establishing a clear simulation strategy and performance evaluation.

Response: See presentation Y. Luo.

- Consider solutions to outstanding optics and lattice optimizations in the tracking studies.

Response: Nonlinear chromaticity corrections included in simulations. C. Montag/S. Tepikian developed lattices with correct phase advance between IP8 and IP10

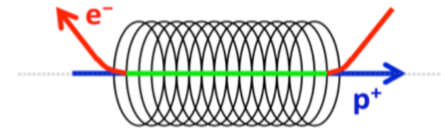
- The simulation studies should include an evaluation of strong-strong beam-beam effects, including coherent motion.

Response: Not yet. With TEL experience do not expect problems but plan to do (new Toohig fellow S. White). Still concentrating on weak-strong problems (presentation Y. Luo).

- Add bunch length effects to the beam-beam and electron lens simulations.

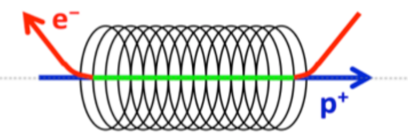
Response: Done.

RHIC electron lens – summary



- Head-on beam-beam effect reduces proton beam lifetime
  observe bunches with 1 vs. 2 collision
- With partial head-on beam-beam compensation using electron lenses expect up to 2x more luminosity
  aim to compensate for 1 of the 2 collisions,
  also requires polarized source and RHIC upgrades (under way)
- Two electron lenses under construction
  both located in IR10, with mutually compensating 6 T superconducting main solenoids, 0.5-1 A DC e-beam
- Plan installation in summer 2012
  for commissioning in Run-13

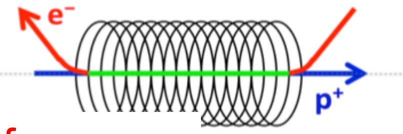
History of head-on beam-beam compensation

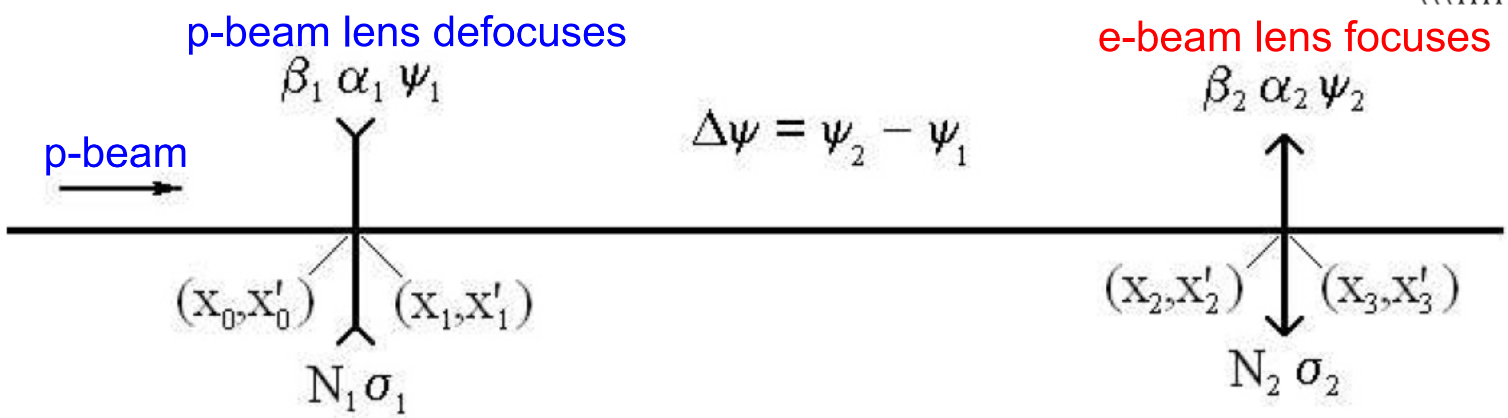


- Compensation schemes (S. Peggs, Handbook):
  1. Direct space charge compensation (4 beams)
  2. Indirect space charge compensation (electron lenses) ← **considered for RHIC**
  3. Betatron phase cancellation between neighboring IPs

- Proposals/studies of head-on beam-beam compensation to date:
  - COPPELIA ➔ 4-beam (J.E. Augustine, HEACC, 1969)
  - DCI ➔ 4-beam (G. Arzelia et al., HEACC, 1971) ➔ **only real attempt so far**
  - CESR ➔ e-lens (R. Talman, unpublished, 1976)
  - SSC ➔ e-lens (E. Tsyganov et al., SSCL-PREPRINT-519 ,1993)
  - LHC ➔ e-lens (E. Tsyganov et al., CERN SL-Note-95-116-AP, 1995)
  - Tevatron ➔ e-lens (Shiltsev et al., PRST-AB, 1999)
  - e^+e^- collider ➔ 4-beam (Y. Ohnishi and K. Ohmi, Beam-Beam’03, 2003)
  - Electron-ion collider ➔ e-lens (C. Montag and W. Fischer, PRST-AB, 2009)

Head-on beam-beam compensation concept





Exact compensation if $x_3(N_1,N_2) = x_3(0,0)$ and $x'_3(N_1,N_2) = x'_3(0,0)$:

1. Short p-beam and e-beam (i.e. zero phase advance during p passage), and
2. Same amplitude dependent force in p-beam and e-beam lens, and
3. Phase advance between p-beam and e-beam lens is $\Delta\Psi = k\pi$, and
4. No nonlinearities between p-beam and e-beam lens

Condition 2 cannot be realized with magnets, requires an electron beam